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The Role of Pendimethalin in the Integrated Management of Propanil-Resistant *Echinochloa colona* in Central America*

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Abstract: Pre-emergence activity of pendimethalin on propanil-resistant jungle rice (*Echinochloa colona*) was demonstrated in glasshouse trials. Both susceptible and resistant populations, collected from Costa Rica, were controlled by 1·25 kg ha^{-1}, the usual application rate used in the field where *Rottboellia cochinchinensis* is also a problem. When applied post-emergence, propanil performance was improved by the addition of low doses of pendimethalin to the herbicide mixture. A propanil-resistant selection was controlled by 0·23 kg ha^{-1} pendimethalin + 0·54 kg ha^{-1} propanil at the one-to-two leaf stage, and 0·23 kg ha^{-1} pendimethalin + 1·08 kg propanil at the three-to-four leaf stage compared to 1·08 kg and 2·16 kg ha^{-1} respectively when propanil was applied alone. This suggests that pendimethalin improves post-emergence control in the field compared to the standard propanil treatment and can provide residual pre-emergence control of late-germinating individuals, so reducing the propanil selection pressure. For effective jungle rice control, growers apply propanil (3·84 kg ha^{-1}) at 10 and 20 days after planting (DAP) followed by one application of fenoxaprop-P-ethyl (0·045 kg ha^{-1}) at 35 DAP. Field experiments, conducted in dry-seeded upland rice in southern Costa Rica, demonstrated that under high jungle-rice population pressure, one application of pendimethalin at 1·5 kg ha^{-1} provided an effective replacement for propanil, resulting in reduced weed-control costs.

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1 INTRODUCTION

Weed management in rice in Latin America depends largely upon post-emergence herbicides, with propanil being the usual choice for the control of the annual jungle rice (*Echinochloa colona* (L.) Link) and other grasses. Repeated propanil use has resulted in the evolution of propanil resistance in jungle rice, now reported to be a problem in Costa Rica, Colombia, El Salvador, Guatemala, Nicaragua and Panama.[1–3] Growers, unaware that inadequate control is due to resistance, have responded by using higher rates or increased frequency of propanil application, or by adopting post-emergence applications of fenoxaprop-P-ethyl, at 30–35 days after planting.[4]

We have demonstrated that propanil-resistant jungle rice biotypes, in comparison to susceptible biotypes, have elevated levels of aryl acylamidase which rapidly metabolises propanil to 3,4-dichloroaniline.[5] This primary metabolite is phytotoxic, but its accumulation in resistant plants appears to be limited by rapid glucosylation and/or incorporation into lignin.[6] Possible approaches to managing propanil-resistant jungle rice include restoring propanil activity by the use of synergists which inhibit aryl acylamidase activity and the further metabolism of 3,4-dichloroanaline,[7] and using herbicides with alternative modes of action. The evolution of resistance to fenoxaprop-P-ethyl, in a population of jungle rice from Costa Rica which had been exposed to acetyl co-enzyme A carboxylase-inhibiting herbicides for just three seasons,[8] emphasises the need to reduce the selection pressure from single modes of action. A tank mix of propanil with pendimethalin is used in the USA to control propanil-resistant barnyard grass, *E. crus-galli* (L.) Beauv.[9] This combination has been used for some time in Costa Rica to control itchgrass (*Rottboellia cochinchinensis* (Lour.) Clayton) infestations in rice. While generally good agreement between the propanil use history and the degree of jungle rice resistance has been found in Costa Rica, one study noted two sites where propanil had been used for more than 15 years, at which the jungle rice was barely more than 1·5 times more resistant than the susceptible control population.[3] Pendimethalin had been used regularly at these sites in addition to propanil and this appeared to have delayed the evolution of resistance. In this paper we report on the response of jungle rice populations to pendimethalin and discuss how it may be incorporated into a resistance management programme.

2 MATERIALS AND METHODS

2.1 Glasshouse trials

The propanil-resistant samples (PR) of jungle rice used in this study had been collected from fields near Parrita, Puntarenas Province, Costa Rica, where propanil had been used for about 20 years. In previous tests these samples, 93.002 and 93.011, had survived 5·6 kg ha^{-1} propanil applied to plants with three or four leaves. The susceptible sample (PS), killed in glasshouse tests by 2·0 kg ha^{-1} propanil, came from a field in Guanacaste Province which had been in rice cultivation for five years with propanil used just twice. Jungle rice seeds were pre-germinated prior to planting in 9-cm diameter pots in a sandy loam soil, amended with a slow-release fertiliser (15% N) at a dose of 3·3 g litre^{-1}. Seedlings were thinned to three plants per plot after emergence, sub-irrigated and maintained in a glasshouse at 30°C during the day, 28°C at night, with 85% relative humidity and a 16-h photoperiod. All herbicides were applied with a laboratory track sprayer, fitted with a 'Spray Systems' 8001 nozzle, calibrated to deliver 200 litre ha^{-1}. Pre-emergence applications were made immediately after planting pre-germinated seed which was covered by 1 cm of soil to ensure uniform depth. The soil was moistened evenly prior to spraying. After spraying, pots were arranged in the glasshouse in randomised complete blocks with at least three replicates.

2.2 Field trials

Field trials were conducted on two farms in Parrita, Costa Rica, between 1994 and 1996 to study possible tactics for integrated control of jungle rice in rice. In-crop control treatments were two applications of propanil 360 g litre^{-1} EC ('Stam' F-34, Rohm and Haas; 3·84 kg AI ha^{-1}) at 10 and 20 days after sowing (DAS) followed by one application of fenoxaprop-P-ethyl ('Furore' 1, AgrEvo; 45 g AI ha^{-1}) at 35 DAS, the conventional herbicide programme in the area, compared to a modified herbicide scheme consisting of a single application of pendimethalin 500 g litre^{-1} EC ('Prowl' 500 EC, American Cyanamid; 1·5 kg AI ha^{-1}) at 6 DAS followed by one application of fenoxaprop-P-ethyl. At the second site (Pelicano), the propanil applications were replaced by a single application of quinclorac WP ('Facet', BASF; 0·35 kg AI ha^{-1}) in 1996 due to high resistance to propanil in the jungle rice population at this location. Quinclorac had previously been shown to be an effective treatment for propanil-resistant jungle rice control in pot trials in UK and in the field in Costa Rica. Herbicides were applied in 200 litre ha^{-1} of water with a compressed air plot sprayer.

3 RESULTS

3.1 Glasshouse trials

Two propanil-resistant and one susceptible sample of jungle rice were susceptible to pendimethalin applied

TABLE 1
Effect of Pre-emergence Application of Pendimethalin on the Height and Vigour of Emerging Seedlings of Three Samples of *Echinochloa colona* from Costa Rica 10 Days after Treatment

Echinochloa *sample*[b]	*Seedling height (% of untreated) (±SE) [vigour]*[a]				
	Pendimethalin (kg ha^{-1})				
	0·156	*0·312*	*0·625*	*1·250*	*2·500*
93.002-PR[c]	30 (±5·5) [2·5]	9·8 (±0·7) [1·7]	10·2 (±2·1) [1·5]	7·6 (±0·7) [1·5]	5·8 (±0·09) [0·7]
93.011-PR[d]	58·6 (±6·2) [6·5]	39·4 (±5·9) [4·4]	30 (±5·9) [4·4]	18·0 (±3·5) [2·5]	6·0 (±0·6) [1·8]
93.013-PS[e]	18·4 (±4·4) [3·4]	16·7 (±5·9) [2·2]	17·8 (±8) [2·0]	6·9 (±2·9) [1·0]	2·6 (±0·8) [0·6]

[a] Visual assessment using a 0–7 scale.[10] 7 = indistinguishable from control, 4 = considerable desiccation, 3 = desiccated, but apparently still making some growth, 2 = alive, with some green tissue, 1 = moribund but not all tissue dead, 0 = completely dead.
[b] PR = propanil-resistant; PS = propanil-susceptible.
[c] Mean height of untreated plants = 92·1(±9·3) mm.
[d] Mean height of untreated plants = 131·0(±5·1) mm.
[e] Mean height of untreated plants = 132·2(±6·8) mm.

pre-emergence (Table 1). Two samples, 93.002 (PR) and 93.103 (PS) showed little development after emergence following treatment with 0·312 kg ha^{-1} of the herbicide while growth of 93.011 (PR) was inhibited at and above 1·2 kg ha^{-1}. Applied post-emergence, pendimethalin alone at 0·92 kg ha^{-1} killed a propanil-resistant sample. Older plants with three or four leaves at spraying were also killed at this application rate 16 days after treatment, while the propanil-susceptible sample (93.013), although severely inhibited, survived 1·84 kg ha^{-1} (Figs 1 and 2). At the one-to-two leaf stage, the resistant sample was controlled by between 1·08 and 2·16 kg ha^{-1} propanil alone, also by 0·23 kg ha^{-1} pendimethalin + 0·54 kg ha^{-1} propanil; there was considerable growth inhibition when the propanil content of the mixture was reduced to 0·27 kg ha^{-1}. Simultaneous application of the two herbicides resulted in the control of jungle rice at the three-to-four leaf stage with lower rates (Fig. 2). At this growth stage, between 2·16 and 4·3 kg ha^{-1} propanil was required to kill the resistant sample. This was controlled by 1·08 kg ha^{-1} propanil when 0·23 kg ha^{-1} pendimethalin was added to the spray mixture.

3.2 Field trials

A single application of 1.5 kg ha^{-1} pendimethalin at 6 DAS resulted in significantly better ($P > 0·05$) jungle

TABLE 2
Effect of Propanil and Pendimethalin on *Echinochloa colona* Infestation when applied Post-Emergence in Dry-Seeded Rice under Field Conditions in Costa Rica.

Location	*Herbicide programme*[a]	*1994*		*1995*		*1996*	
		Number of plants m^{-2} at days after sowing[b]					
		6	*30*	*6*	*30*	*6*	*30*
Bejuco	Conventional	287 a	21 a	22 a	20 a	25 a	5 a
	Modified	246 a	9 b	22 a	7 b	22 a	4 b
Pelicano	Conventional[c]	—	—	72 a	40 a	100 a	0 a
	Modified	—	—	72 a	11 b	71 a	3 b

[a] Conventional = propanil (3·84 kg ha^{-1}) at 10 and 20 DAS; Modified = pendimethalin (1·5 kg ha^{-1}) at 6 DAS.
[b] Values followed by the same letter within a column at each location are not significantly different based on LSD at $P > 0·05$.
[c] Because of high resistance to jungle rice at this location, a single treatment of quinclorac was substituted for the conventional treatment of two applications of propanil in 1996.

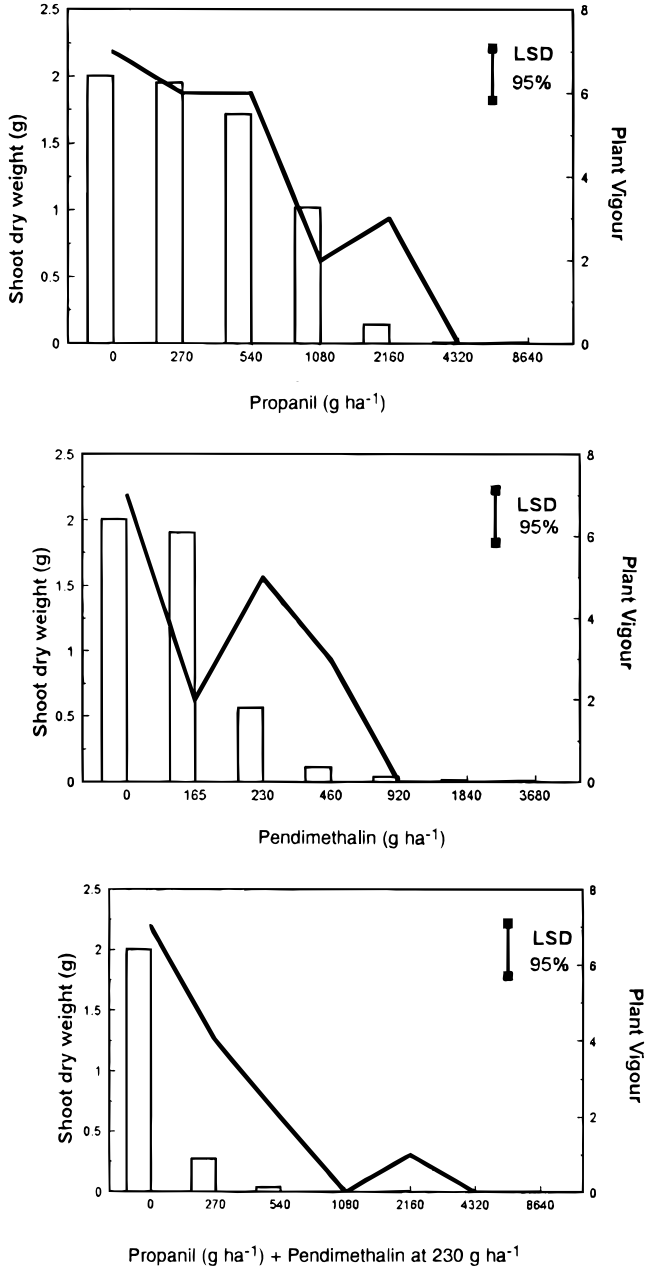

Fig. 1. Effect of propanil and pendimethalin applied at the one-to-two leaf stage, on shoot dry-weight and (——) vigour of propanil-resistant *Echinochloa colona* (93.011), 16 days after treatment.

rice control than two applications of propanil over a three-year period at two sites in Costa Rica (Table 2). When pendimethalin was applied, the most developed jungle rice had two leaves; some plants were yet to emerge. Excellent control was also achieved in 1996 with quinclorac at Pelicano where a high level of propanil resistance had led to increasing numbers of jungle rice plants on plots managed by the conventional propanil-based herbicide programme.

4 DISCUSSION

Pendimethalin is used as an early post-emergence herbicide in rice in Costa Rica in order to control the highly competitive exotic, itchgrass (*R. cochinchinensis*). The glasshouse trials suggest that at the stage and application rate at which pendimethalin is commonly used (1·25 to 1·5 kg ha^{-1} at six days after sowing) there will be both post-emergence activity and residual pre-emergence control of later germinating jungle rice plants. Both propanil-resistant and susceptible populations can be controlled, explaining the lower levels of propanil resistance reported from some sites in Costa Rica where pendimethalin has been tank-mixed with propanil for itchgrass control.[3] The glasshouse trials have also demonstrated that the addition of pendimethalin to the spray mixture also reduces the application rate at which propanil is active against older jungle rice seedlings with three to four leaves. In the field trials, pendimethalin was shown to be an effective replacement for two applications of propanil for in-crop control of jungle rice. This was used in an integrated approach as a follow-up to the control of the first germination flush of the weed with a pre-plant post-emergence broadcast application of glyphosate at 0·72 kg ha^{-1}.[11] With the conventional propanil-based herbicide programme, growers have started to rely on late post-emergence application of fenoxaprop-P-ethyl. Resistance has also been reported to this herbicide in jungle rice in Costa Rica[8] and further work is needed to determine the susceptibility of fenoxaprop-resistant populations to pendimethalin. In addition to *E. colona* and *R. cochinchinensis*, other important grass weeds of rice normally controlled by propanil, including *Digitaria* spp., *Leptochloa filiformis* (Lam.) P. Beauv., *Eleusine indica* (L.) Gaertn., are also controlled by pendimethalin (Valverde, pers. commun.). However some important broadleaf species, including *Physallis* spp., *Phyllanthus* spp., *Jussiaea* spp. and *Euphorbia heterophylla* L., are also susceptible to propanil. Growers commonly use a phenoxy acid herbicide for sedge suppression and this will also be important for broadleaf weed control when pendimethalin is used to replace propanil. Costs have risen as jungle rice control has become increasingly difficult and growers have found it necessary to increase propanil application frequency and to include additional products in the weed control programme. Typical herbicide costs in Costa Rica for two applications of propanil (each at 3·84 kg ha^{-1}) are now US$60; a follow-up application of fenoxaprop-P-ethyl, at a typical grower dose of 45 g ha^{-1} would cost a further $37. As an alternative strategy, quinclorac may be used at 0·35 kg ha^{-1}, costing $78. Including pendimethalin in a herbicide rotation strategy is financially attractive; in the field trials, adequate jungle-rice control was achieved by replacing two applications

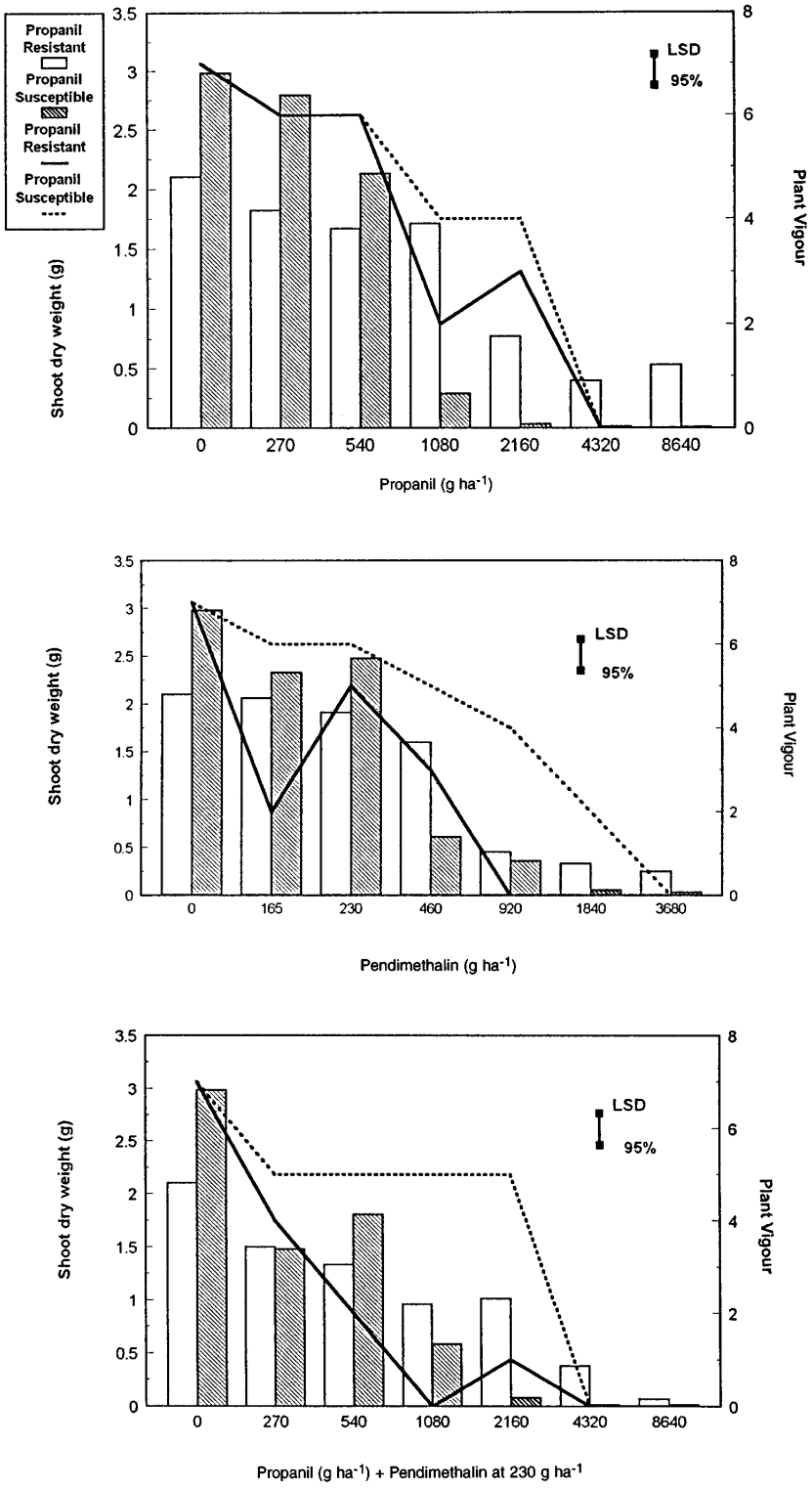

Fig. 2. Effect of propanil and pendimethalin applied at the three-to-four leaf stage, on shoot dry-weight and (——; · · ·) vigour of propanil-resistant (93.011) and propanil-susceptible (93.013) *Echinochloa colona*, 16 days after treatment.

of propanil with one application of pendimethalin (1·5 kg ha^{-1}), costing $34. If growers in Central America are to adopt a rational herbicide resistance management programme, including rotation of herbicides to reduce the selection pressure imposed by any one mode of action, it is important that affordable options are available so that rice produced in the region remains competitive with imported supplies.

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